Mid-Infrared Broadband Modulation Instability and 50 dB Raman Assisted Parametric Gain in Silicon Photonic Wires

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Abstract: We demonstrate broadband modulation instability, > 40 dB parametric amplification with on-chip gain bandwidth > 580 nm, and narrowband Raman-assisted peak on-chip gain exceeding 50 dB, using mid-infrared dispersion-engineered silicon nanophotonic wires.

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1. Introduction

Within the mid-infrared (mid-IR) spectral region near λ = 2200 nm, the silicon nanophotonic wire platform has a strong potential to be used in constructing room temperature, highly efficient, and ultra-compact devices for light generation and amplification through coherent nonlinear optical processes [1-3]. This platform could be an ideal host for a large variety of mid-IR applications including molecular spectroscopy, free-space communication and environmental monitoring [4, 5]. Strong optical confinement in this platform not only enhances the effective nonlinearity by means of reduced optical modal area, but also provides great flexibility in the control of waveguide dispersion that is necessary for processes such as four-wave mixing (FWM) [6]. We have recently reported a 4 mm-long silicon wire mid-IR optical parametric amplifier (OPA) having substantial on-chip gain over a bandwidth of 220 nm [1]. In this work, by utilizing a 2 cm-long dispersion-engineered wire having reduced propagation losses, we demonstrate strong mid-IR parametric fluorescence, or modulation instability (MI), covering a bandwidth > 580 nm around the pump. The observability of intense MI correlates with very large values of on-chip parametric gain, exceeding 40 dB. Moreover, we also demonstrate that on-chip gain can exceed 50 dB in narrow bands assisted by stimulated Raman scattering.

2. Broadband modulation instability, Raman stoke and parametric amplification

The silicon nanophotonic wire was fabricated on a 200 mm silicon-on-insulator (SOI) wafer in a CMOS pilot line at Ghent University-IMEC. It has cross-sectional dimensions of w = 900 nm by h = 220 nm (inset Fig. 1a), and is 2 cm in length. The cladding consists of air above and a 2 μm buried oxide (BOX) below. The waveguide is designed to operate in the fundamental quasi-TE mode, and has low propagation losses < 2.8 dB/cm for wavelengths from 2000 nm to 2500 nm. The engineered waveguide dimensions produce anomalous dispersion conditions (2nd-order dispersion $\beta_2 < 0$) at wavelengths from 1800 nm to 2400 nm as shown in Fig 1(a). Furthermore, this waveguide has small positive 4th-order dispersion ($\beta_4 > 0$) within the same wavelength range. This small positive β_4 term is particularly important for achieving broadband phase matching and therefore broadband parametric amplification. The linear phase mismatch contribution from the small positive β_4 term counteracts the negative β_2 term, resulting in a low total linear phase mismatch ($\Delta k_l \approx \beta_2(\Delta\omega)^2+1/12\ \beta_4(\Delta\omega)^4 \approx 0$) over a broad spectrum around the pump.

The FWM pump is a picosecond pulse train (FWHM ~ 2 ps, repetition rate = 76 MHz) from an optical parametric oscillator operating at λ = 2173 nm, and the probe is a cw signal from a tunable mid-IR laser. Both pump and probe are coupled into single-mode optical fiber, and then multiplexed with a 90/10 fiber coupler. Coupling into/out of the 2 cm-long silicon nanophotonic wire is via edge coupling with lensed tapered fibers (coupling losses ~ 10 dB/facet). Polarization controllers are used to excite the quasi-TE mode with both pump and probe.

The input pump pulse shows a clean spectrum with a signal-to-noise ratio > 75 dB as illustrated by the dashed magenta curve in Figure 1(b). The peak pump power coupled into the waveguide input is ~ 13.5 W. Besides the commonly observed self-phase modulation (SPM) and spectral blue-shift due to residual free carrier dispersion [7], the spectrum of transmitted pump (solid cyan curve of Figure 1(b)) exhibits significant modifications compared with the input spectrum. The spectrum at the waveguide output is characterized by the emergence of a strong broadband MI spectrum extending from 1911 nm to 2486 nm. In addition, a prominent Raman Stokes peak rides on top of the

MI spectrum at a wavelength of 2411 nm, frequency down-shifted from the pump by a Stokes shift of 15.6 THz [8]. In addition, the Raman Stokes is parametrically wavelength-converted to a phase-matched idler term near 1950 nm. Furthermore, the sharp interference pattern visible around both narrowband Raman peaks originates from the phase shift introduced by the dispersion of the Raman susceptibility. This phase shift is superimposed upon the broadband FWM phase matching condition [9, 10], producing spectral fringes where phase matching for MI is disrupted.

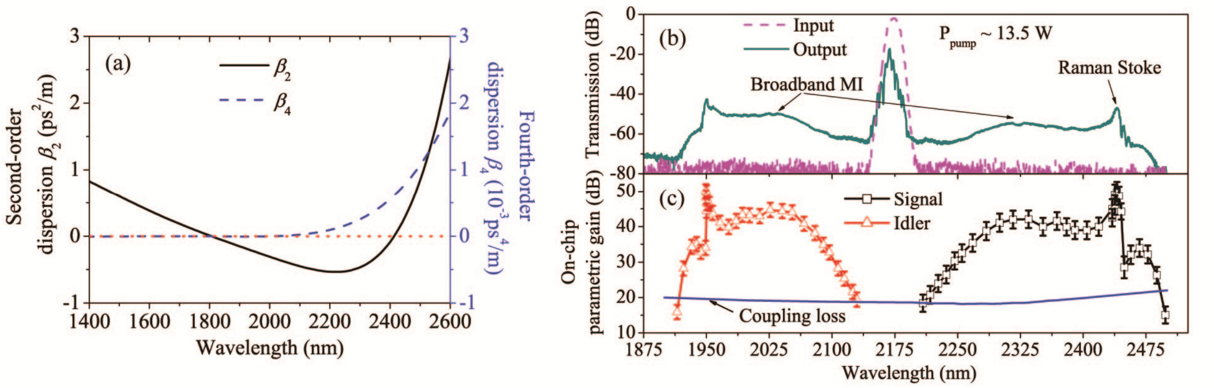

Fig. 1: (a) Second-order (solid black curve) and fourth-order (dashed blue curve) dispersion of fundamental quasi-TE mode for the silicon wire: *w* = 900 nm, *h* = 220 nm. (b) Input (dashed magenta curve) and transmitted (solid cyan curve) pump spectra, illustrating broadband modulation instability and Raman Stokes peak. (c) On-chip parametric gain, exhibiting broadband on-chip amplification over a bandwidth > 580 nm, maximum Raman-assisted gain values of ~ 50 dB, unassisted FWM parametric gain of ~ 40 dB, and peak net off-chip gain > 30 dB.

The visibility here of a strong MI background suggests that the on-chip mid-IR parametric gain available is far larger than demonstrated in previous studies [1], where MI was not observed. The amplification is probed using a cw signal with wavelengths varying from 2209 to 2498 nm (8 nm step size), generating corresponding idler terms from 2129 to 1914 nm. The cw signal power coupled into the waveguide is kept < 0.05 mW to prevent pump depletion. The peak pump power remains the same as in the pump transmission measurement, P_p ~ 13.5 W. Figure 1(c) plots the measured on-chip amplification/conversion gain, defined following the method in [1]. The mid-IR-pumped silicon nanophotonic waveguide OPA exhibits on-chip optical parametric amplification over a bandwidth exceeding 580 nm. Near the Raman peaks, the OPA reaches a maximum Raman-assisted parametric signal/idler gain of ~ 50 dB. The gain profile exhibits an interference pattern around the Raman-assisted peaks related to that seen in the MI spectrum of Figure 1(b). The number of interference fringes observed in Fig. 1(c) is reduced, because the coarse 8 nm wavelength step is not small enough to resolve the fine features. In addition, the OPA shows larger than 40 dB maximum optical gain resulting solely from the parametric FWM process. After compensating all fiber-chip coupling losses from both facets (~ 20 dB, solid blue curve in Figure 1(c)), the OPA shows a net off-chip gain bandwidth of ~ 550 nm with ~ 30 dB Raman-assisted off-chip gain for both signal and idler. In comparison with the results we reported previously on a 4 mm-long silicon wire OPA [1], the peak operating pump power is reduced to less than half. At the same time, the maximum on-chip gain obtained using the 2 cm-long wire here shows an improvement of more than 25 dB, while the on-chip gain bandwidth is more than doubled.

The results here represent a sizeable improvement over prior work on mid-IR-pumped silicon nanophotonic wire optical parametric amplifiers [1]. Moreover, we have shown that judicious dispersion engineering and improved wire loss characteristics can be leveraged to control and improve the bandwidth and gain, perhaps even extending the gain band all the way to telecom wavelengths near 1550 nm.

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